

# **Baryon Acoustic Oscillations and DE Figure of Merit**

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- **BAO as a robust dark energy probe**
- **Forecasting DE FoM from BAO**

# How We Probe Dark Energy

- *Cosmic expansion history  $H(z)$  or DE density  $\rho_X(z)$ :*  
tells us whether DE is a cosmological constant

$$H^2(z) = 8\pi G[\rho_m(z) + \rho_r(z) + \rho_X(z)]/3 - k(1+z)^2$$

- *Cosmic large scale structure growth rate function  $f_g(z)$ , or growth history  $G(z)$ :*  
tells us whether general relativity is modified

$$f_g(z) = d\ln \delta / d\ln a, \quad G(z) = \delta(z) / \delta(0)$$

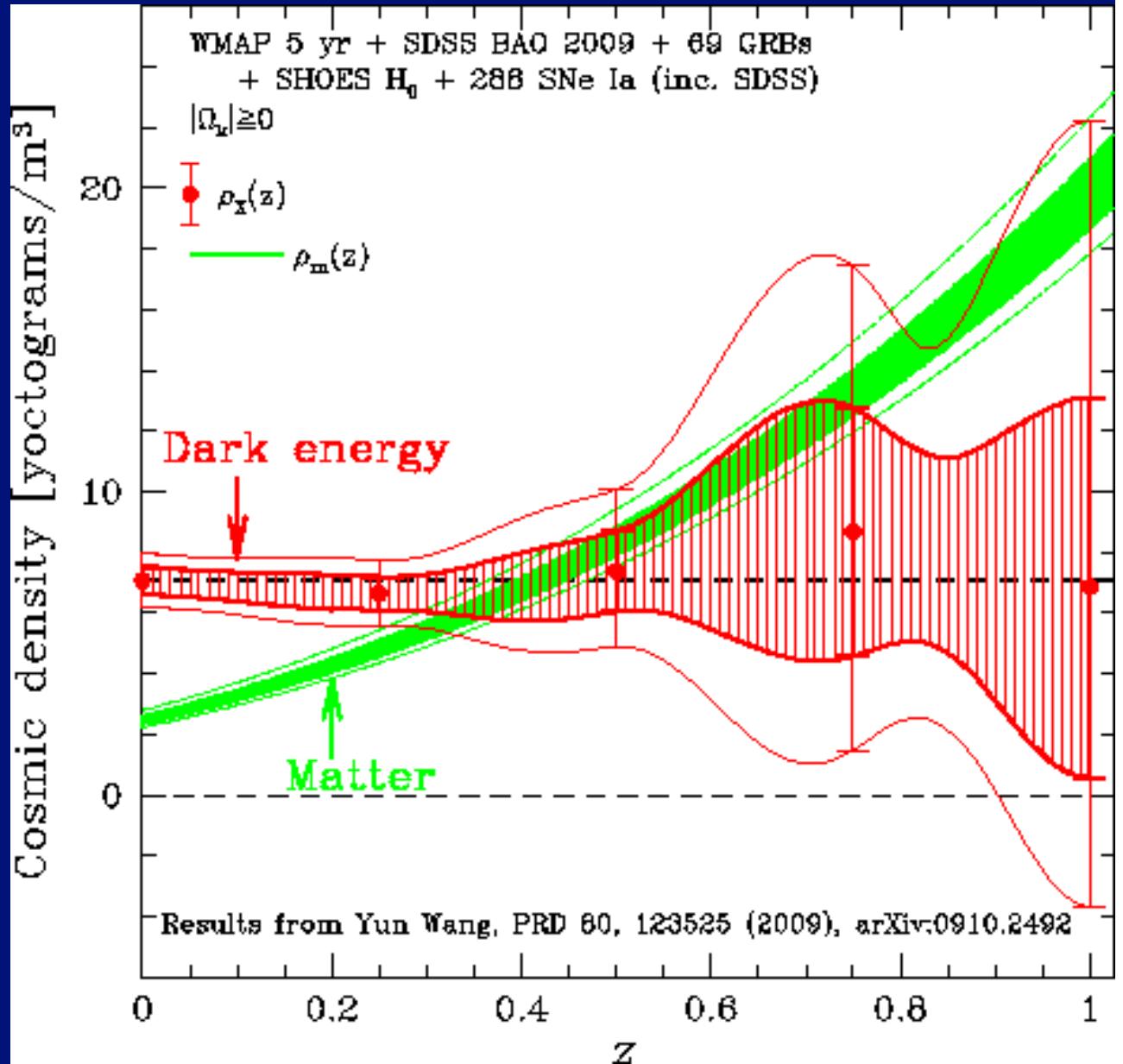
$$\delta = [\rho_m - \langle \rho_m \rangle] / \langle \rho_m \rangle$$

# Current Dark Energy Constraints

Wang (2009)

1 yoctogram= $10^{-24}$  g

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# Observational Methods for Probing Dark Energy

- Measure two functions of redshift  $z$ :
  - cosmic expansion rate  $H(z)$  tells us whether dark energy is a cosmological constant
  - growth rate of cosmic large scale structure  $f_g(z)$  [or growth factor  $G(z)$ ] tells us whether gravity is modified, given  $H(z)$
- Use three main methods:
  - SNe Ia (Standard Candles): method through which DE was discovered; independent of clustering of matter, probes  $H(z)$ .
  - Baryon Acoustic Oscillations (Standard Ruler): calibrated by CMB, probes  $H(z)$ . Redshift-space distortions from the same data probe  $f_g(z)$ .
  - Weak Lensing Tomography and Cross-Correlation Cosmography: probe a combination of  $G(z)$  and  $H(z)$ .

# The Origin of BAO

- At the last scattering of CMB photons, the acoustic oscillations in the photon-baryon fluid became frozen and imprinted on
  - CMB (acoustic peaks in the CMB)
  - Matter distribution (BAO in the galaxy power spectrum)
- The BAO scale is the sound horizon scale at the drag epoch
  - The drag epoch occurred shortly after decoupling of photons, when photon pressure could no longer prevent gravitational instability of baryons.
  - WMAP data give  $s = 153.2 \pm 1.7$  Mpc,  $z_d = 1020.5 \pm 1.6$   
*(Komatsu et al. 2010)*

# BAO as a Standard Ruler

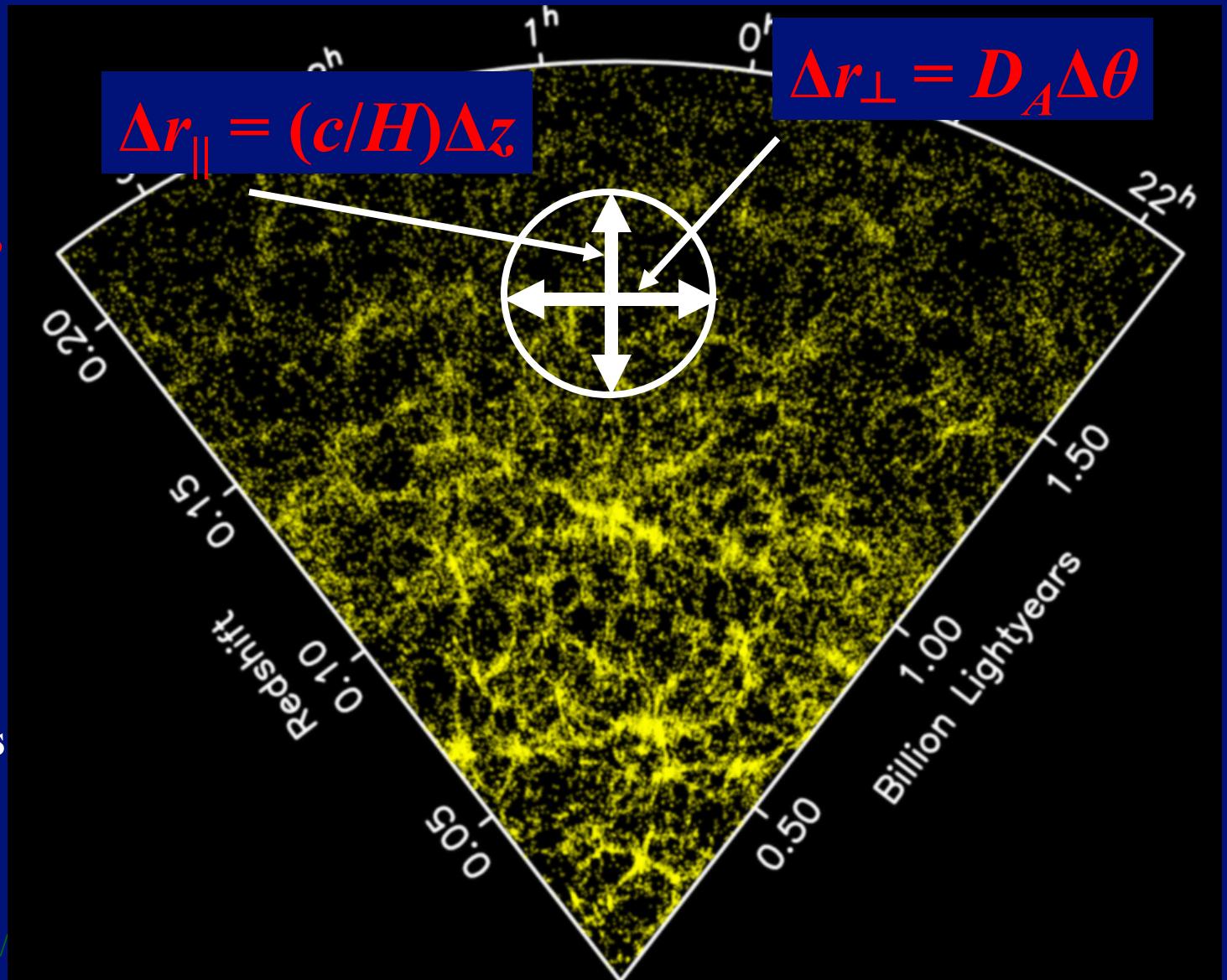
Blake & Glazebrook 2003

$\Delta r_{\parallel} = \Delta r_{\perp} = 148 \text{ Mpc}$  = standard ruler  
Seo & Eisenstein 2003

BAO “wavelength”  
in radial direction  
in slices of  $z$  :  $H(z)$

BAO “wavelength”  
in transverse  
direction in slices  
of  $z$  :  $D_A(z)$

BAO systematics:  
→ Bias  
→ Redshift-space  
distortions  
→ Nonlinear effects



# Differentiating dark energy and modified gravity

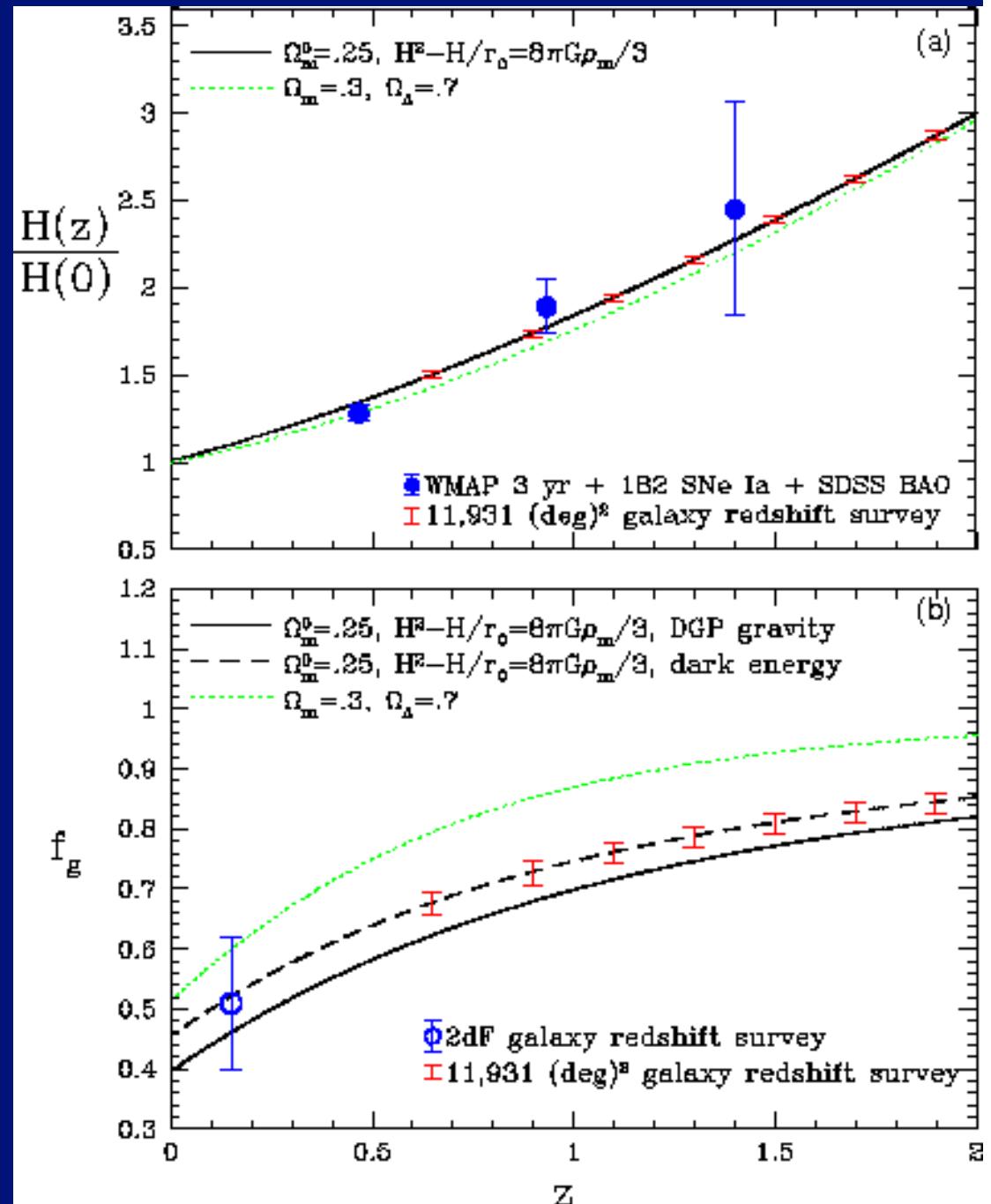
Measuring redshift-space distortions  $\beta(z)$  and bias  $b(z)$  allows us to measure  $f_g(z) = \beta(z)b(z)$

$$[f_g = d\ln \delta / d\ln a]$$

$H(z)$  and  $f_g(z)$  allow us to differentiate dark energy and modified gravity.

Wang (2008)

Yun Wang, 3/2011

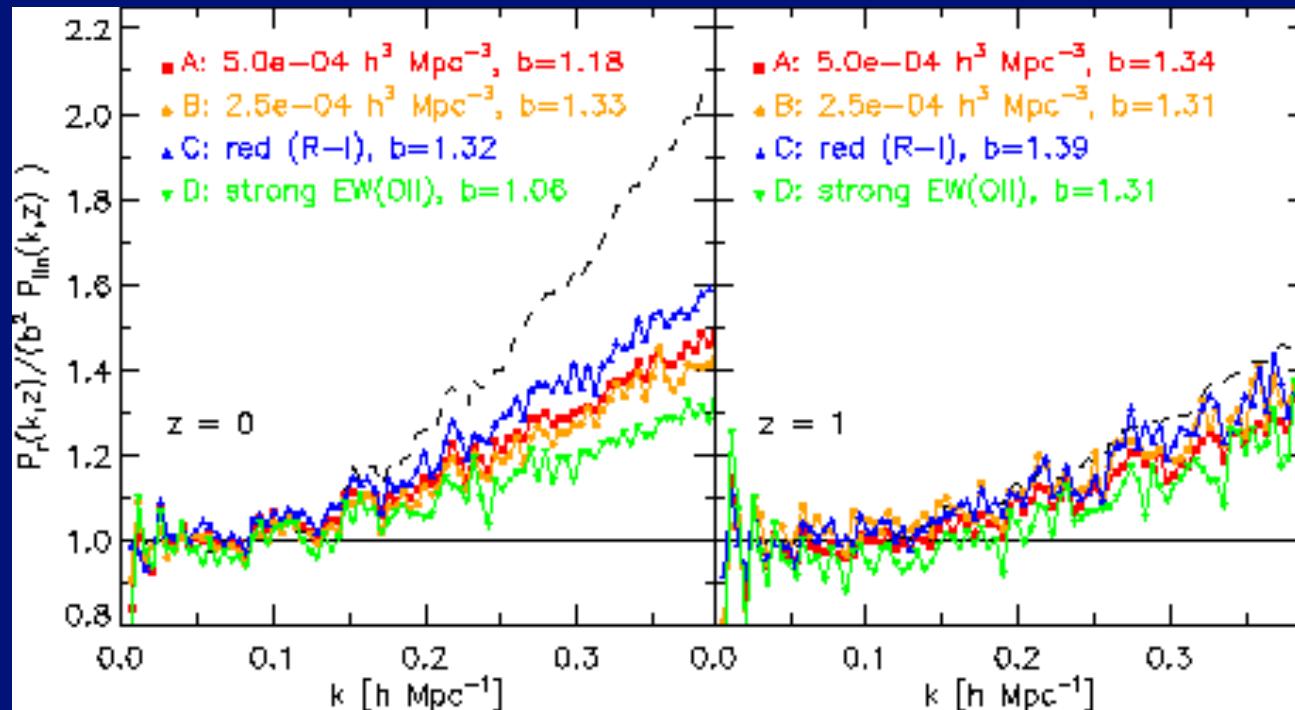


# **BAO Avantages and Challenges**

- **Advantages:**
  - Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).
  - Systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling of data.
- **Challenges:**
  - Full modeling of systematic uncertainties
  - Translate forecasted performance into reality

# BAO Systematic Effect: Galaxy Clustering Bias

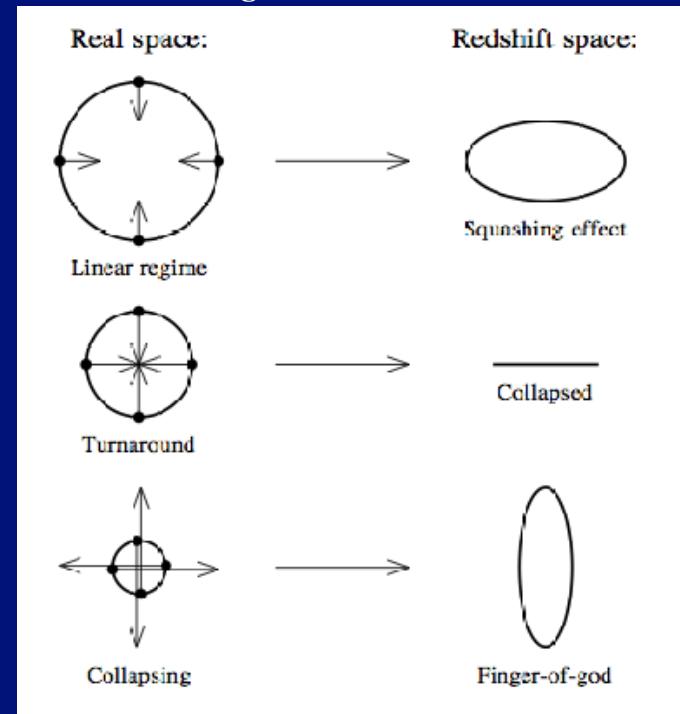
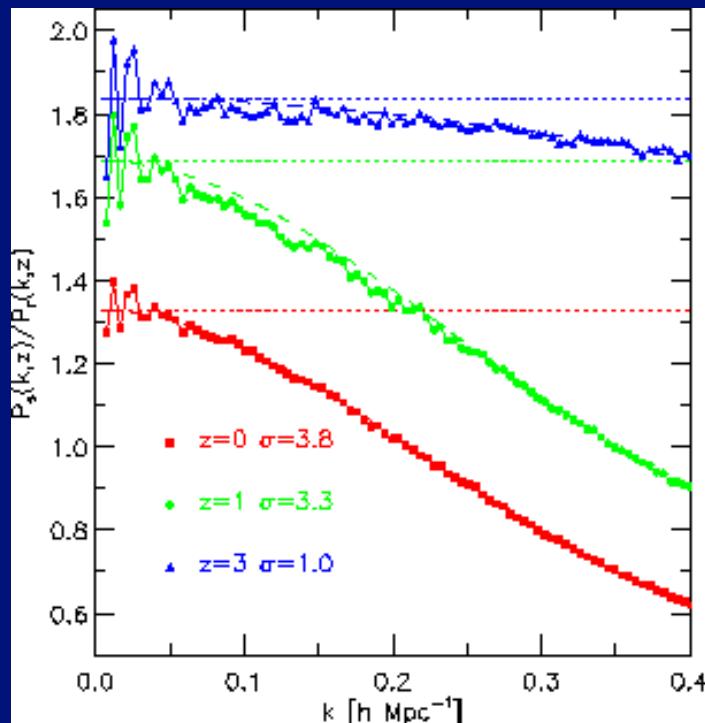
- How galaxies trace mass distribution
  - Could be scale-dependent
  - Only modeled numerically for a given galaxy sample selection (Angulo et al. 2008)



Ratio of galaxy power spectrum over linear matter power spectrum  
Horizontal lines: no scale dependence in bias. Dashed lines: model

# BAO Systematic Effect: Redshift Space Distortions

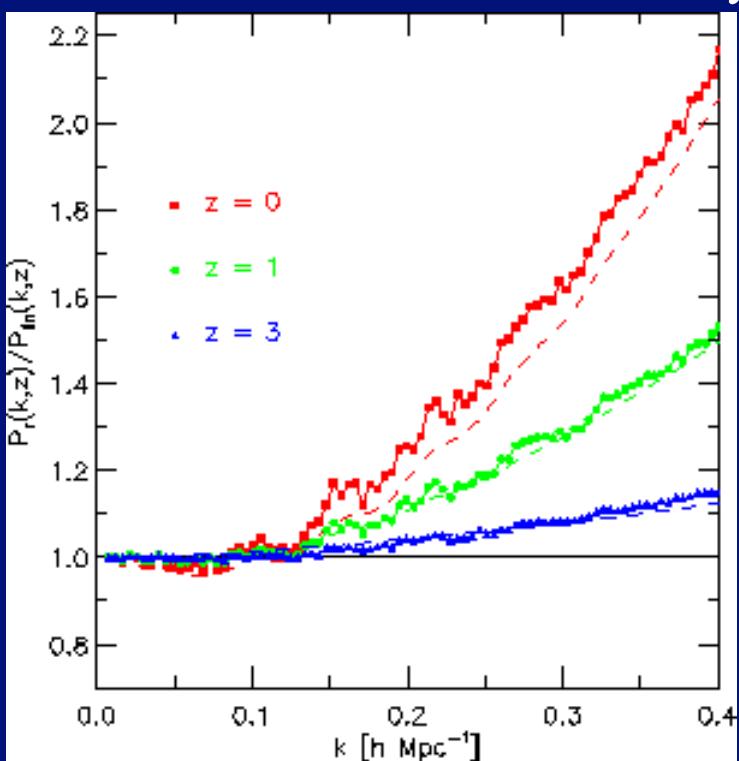
- Artifacts not present in real space
  - Small scales: smearing due to galaxy random motion (“Finger of God” effect)
  - Large scales: coherent bulk flows (out of voids and into overdense regions). These boost BAO; can be used to probe growth rate  $f_g(z)$



→ Left: Ratio of redshift-space and real-space power spectra. Horizontal lines: coherent bulk flows only. Dashed lines: model (Angulo et al. 2008)

# BAO Systematic Effect: Nonlinear Gravitational Clustering

- Mode-coupling
  - Small scale information in  $P(k)$  destroyed by cosmic evolution due to mode-coupling (nonlinear modes); intermediate scale  $P(k)$  also altered in shape
  - Its effect can be reduced by:
    - (1) Density field reconstruction (Eisenstein et al. 2007)
    - (2) Extracting “wiggles only” constraints (discard  $P(k)$  shape info)
    - (3) Full modeling of correlation function (Sanchez et al. 2008)

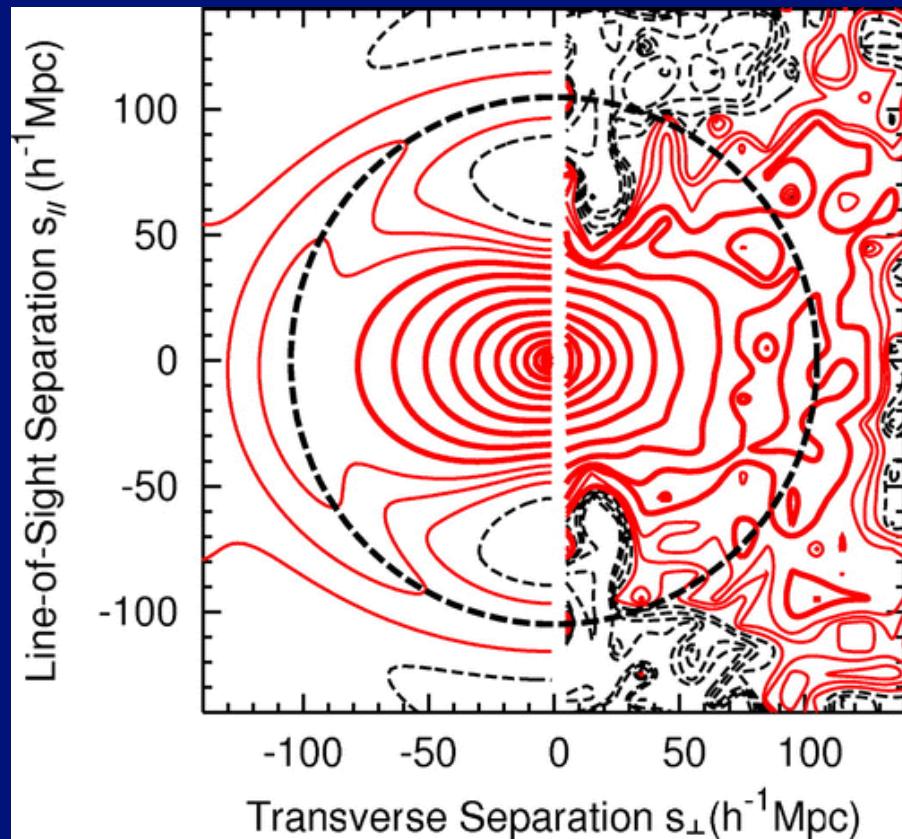


–mostly untested on real data

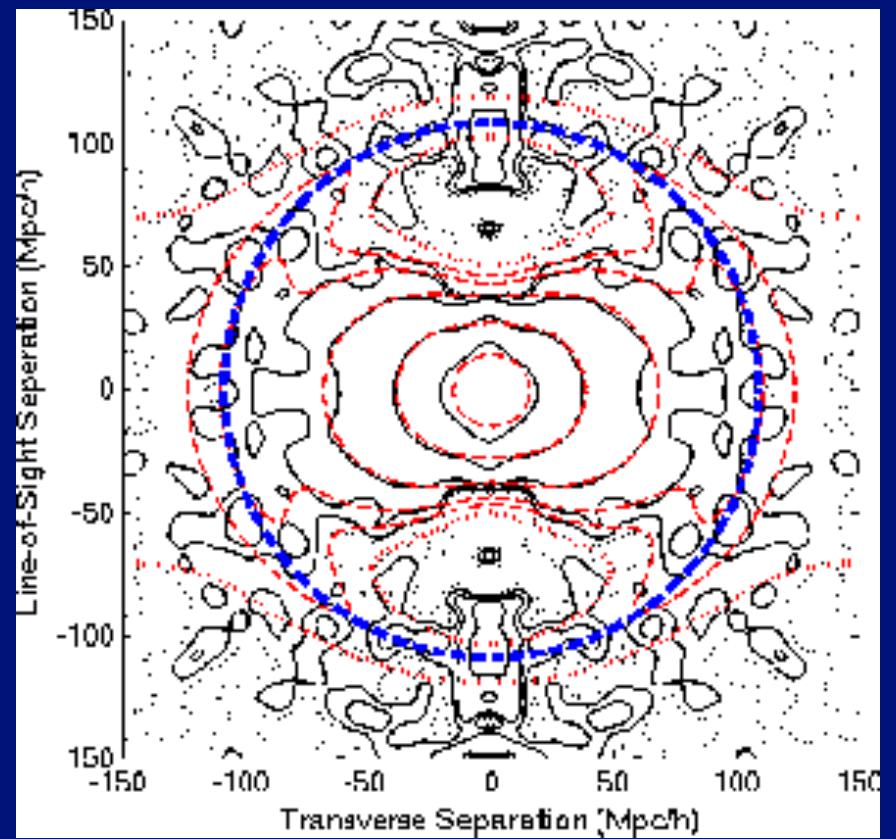
Ratio of nonlinear and linear  $P(k)$   
Horizontal line: no nonlinearity  
Dashed lines: model  
Dark matter only  
(Augulo et al. 2008)

# 2D Galaxy Clustering of SDSS LRGs

*Okumura et al. (2008)*

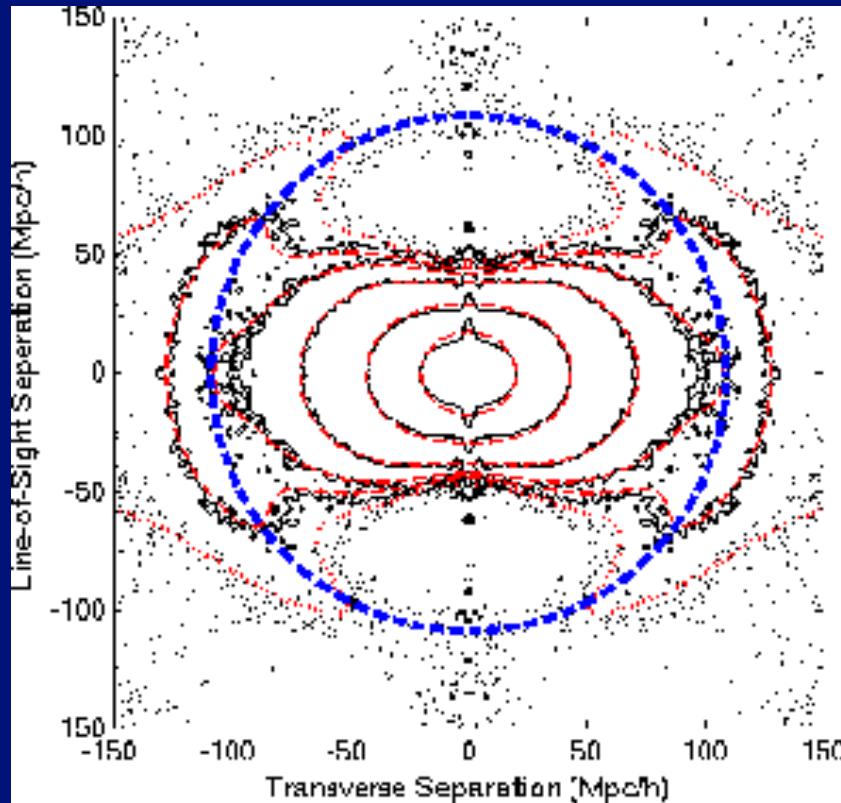


*Chuang & Wang, arXiv:1102.2251*



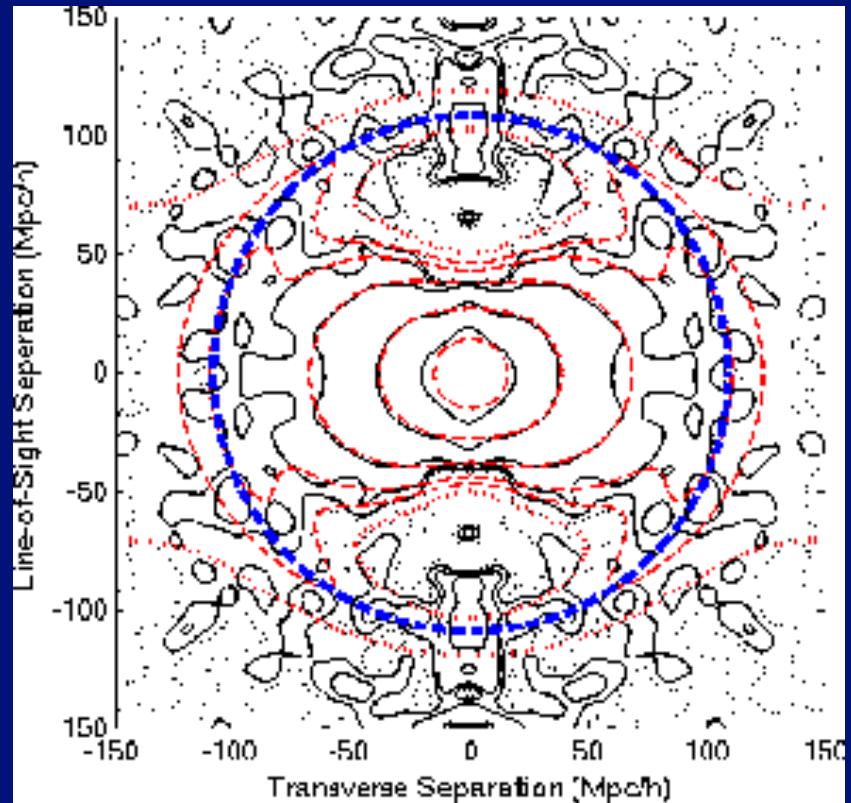
# First Measurements of $H(z)$ and $D_A$ ( $z$ ) from Data

Average of 160 LasDamas mock catalogs



*Chuang & Wang, arXiv:1102.2251*

SDSS LRG catalog



$$H(z = 0.26) = 78.2_{-4.3}^{+4.2} \text{ km s}^{-1}\text{Mpc}^{-1}$$

$$D_A(z = 0.26) = 916_{-45}^{+46} \text{ Mpc}$$

# DETF FoM

- DETF figure of merit  
=  $1/[\text{area of 95\% C.L. } w_0-w_a \text{ error ellipse}],$   
for  $w_X(a) = w_0 + (1-a)w_a$
- Pivot Value of a:  
At  $a=a_p$ ,  $w_p = w_0 + (1-a_p)w_a$ .  
Making  $\langle \delta w_p \delta w_a \rangle = 0$  gives  $1-a_p = -\langle \delta w_0 \delta w_a \rangle / \langle \delta w_a^2 \rangle$ :  
 $\text{DETF FoM} = 1/[6.17\pi \sigma(w_a) \sigma(w_p)]$
- $\text{FoM}_r = 1/[\sigma(w_a) \sigma(w_p)]$
- $a_p$  is different for each survey, thus  $w_p$  refers to a different property of DE in each survey.

- Given a set of DE parameters, what is the simplest, intuitive, and meaningful way to define a FoM?
- What are the sets of minimal DE parameters that we should use in comparing different DE projects?

# Generalized FoM

- For parameters  $\{f_i\}$ :

$$\text{FoM}_r = 1/[\det \text{Cov}(f_1, f_2, f_3, \dots)]^{1/2}$$

- Can be easily applied to both real and simulated data

- DETF  $\text{FoM}_r = 1/[\sigma(w_a)\sigma(w_p)]$   
 $= 1/[\det \text{Cov}(w_0 w_a)]^{1/2}$

*Wang (2008)*

# What Parameters to Use:

- Two considerations:
  - Simple, clear, intuitive physical meaning
  - Minimally correlated
- 2 Parameter Test:  $\{w_0, w_{0.5}\}$ 
$$w_X(a) = 3w_{0.5} - 2w_0 + 3(w_0 - w_{0.5})a$$
$$w_0 = w_X(z=0), w_{0.5} = w_X(z=0.5)$$
- 3 Parameter Test:  $\{X_{0.5}, X_{1.0}, X_{1.5}\}$ 

value of  $X(z) = \rho_X(z)/\rho_X(z=0)$  at  $z = 0.5, 1.0, 1.5$   
simplest smooth interpolation: polynomial

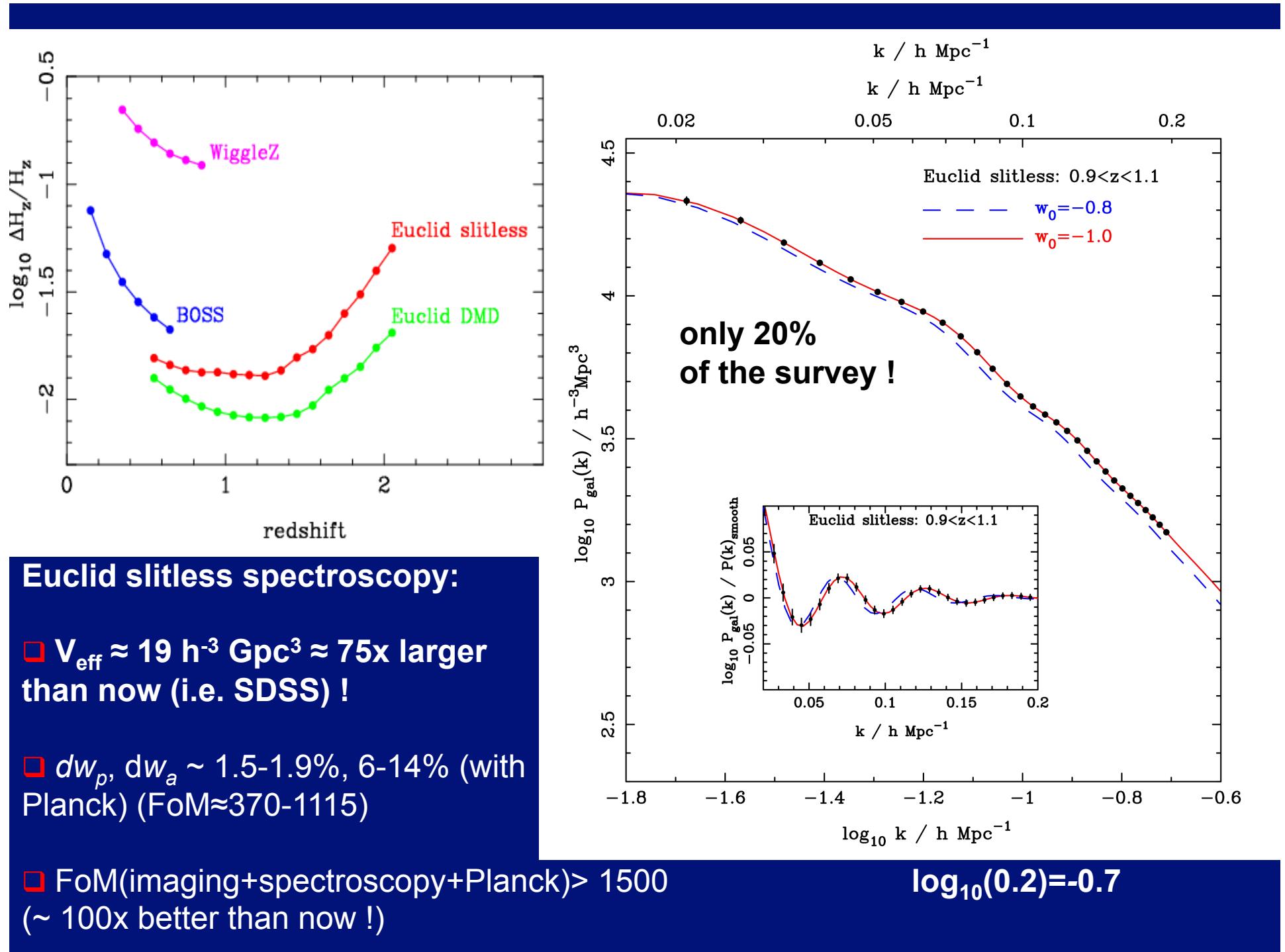
# DE Forecasting from BAO

- Propagate the measurement errors in  $\ln P_g(k)$  into measurement errors for the parameters  $p_i$ :

$$F_{ij} = \int_{k_{\min}}^{k_{\max}} \frac{\partial \ln P_g(\mathbf{k})}{\partial p_i} \frac{\partial \ln P_g(\mathbf{k})}{\partial p_j} V_{eff}(\mathbf{k}) \frac{d\mathbf{k}^3}{2(2\pi)^3}$$

- $\Delta \ln P_g(k) \propto [V_{\text{eff}}(k)]^{-1/2}$

$$\begin{aligned} V_{eff}(\mathbf{k}) &= \int d\mathbf{r}^3 \left[ \frac{n(\mathbf{r}) P_g(k, \mu)}{n(\mathbf{r}) P_g(k, \mu) + 1} \right]^2 \\ &= \left[ \frac{n P_g(k, \mu)}{n P_g(k, \mu) + 1} \right]^2 V_{\text{survey}} \end{aligned} \quad \mu = \mathbf{k} \cdot \mathbf{r} / kr$$



# Two Approaches:

- “Full  $P(k)$ ” method:  
parametrize  $P(k)$  using  
 $[H(z_i), D_A(z_i), f_g(z_i)\sigma_{8m}(z_i), \sigma_{8g}(z_i), P_{\text{shot}}^i, n_S, \Omega_m h^2, \Omega_b h^2]$
- BAO “wiggles only”:  
$$P(k) \propto P(k_{0.2}, \mu | z) [\sin(x)/x] \cdot \exp[-(k\Sigma_s)^{1.4} - k^2 \Sigma_{nl}^2/2]$$
$$x = (k_\perp^2 s_\perp^2 + k_\parallel^2 s_\parallel^2)^{1/2}$$
$$p_1 = \ln s_\perp^{-1} = \ln(D_A/s); p_2 = \ln s_\parallel = \ln(sH).$$
  - Assumes that the shape of  $P(k)$  (and BAO) are fixed by CMB
  - Inclusion of growth info is precluded by construction

# FoM( $w_0, w_a$ )

	P(k)	+Planck	P(k)+ $f_g$	+Planck
Euclid	48.25	369.58	148.93	1114.91
Euclid+BOSS	52.22	386.53	166.62	1165.83

## Euclid-NIS+Planck

	$d w_0$	$d w_a$	$d w_p$	FoM( $w_0, w_a$ )
P(k)	0.067	0.140	0.0193	369.58
P(k)+ $f_g$	0.023	0.061	0.0148	1114.91

Wang et al. (2010)

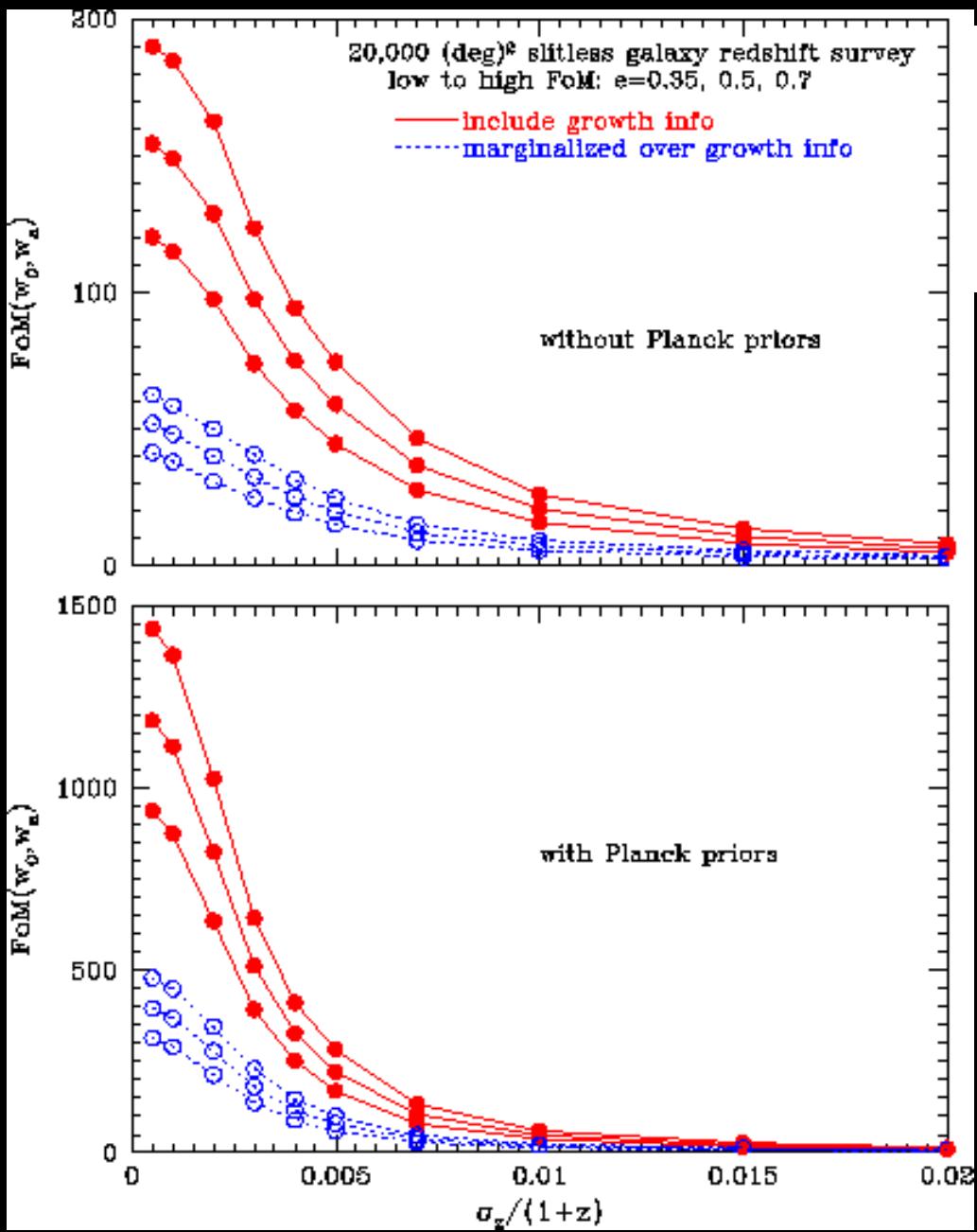
# FoM( $\mathbf{X}_{0.67}, \mathbf{X}_{1.33}, \mathbf{X}_2$ )

	P(k)	+Planck	P(k)+ $f_g$	+Planck
Euclid	421.26	3487.41	2979.51	26659.23
Euclid+BOSS	449.85	3639.72	3206.81	27664.98

Wang et al. (2010)

$$\text{FoM}\{f_1, f_2, \dots\} = \{\det[\text{Cov}(f_1, f_2, \dots)]\}^{-1/2}$$

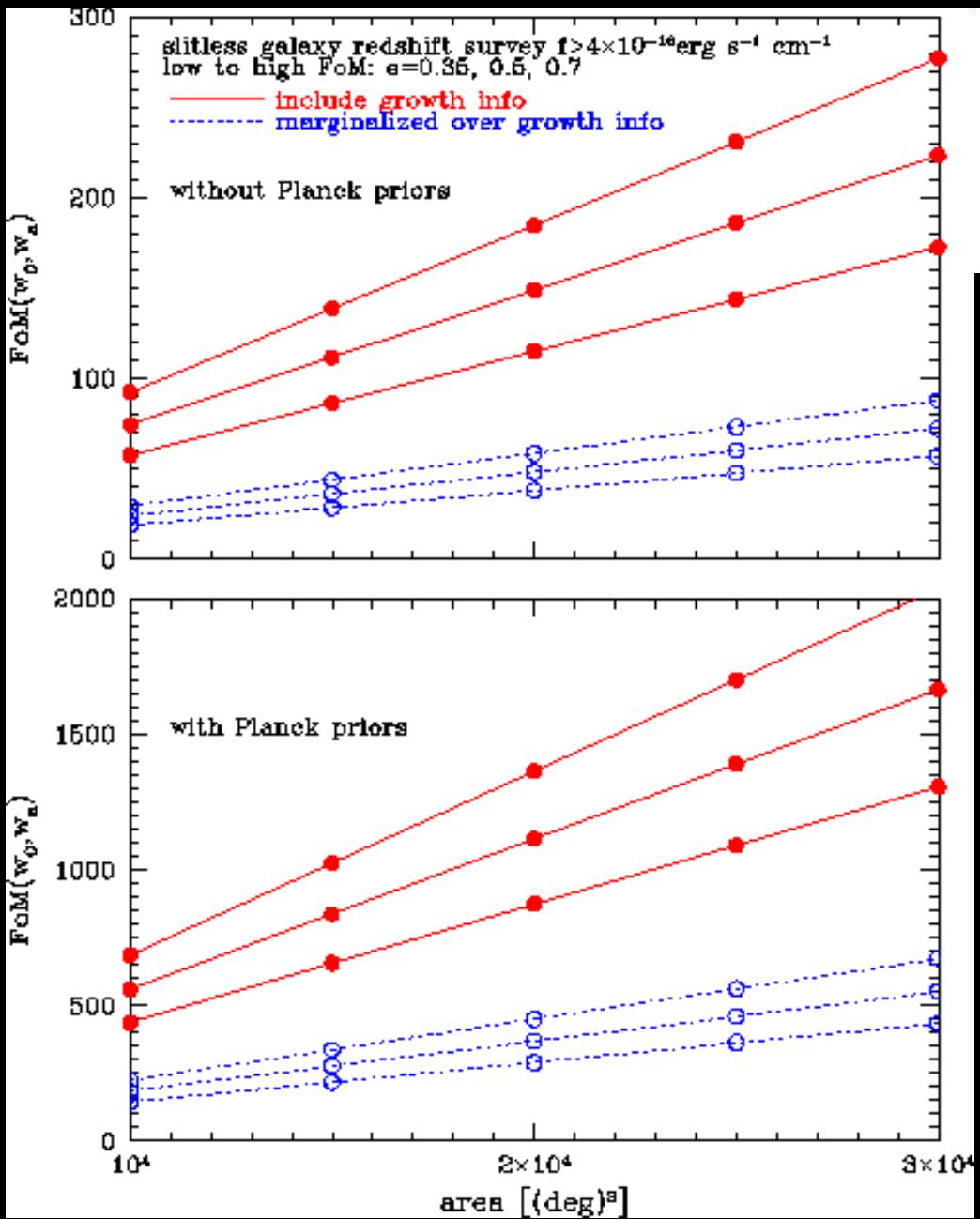
# Figure of Merit vs redshift accuracy



Euclid Baseline:  $f > 4 \times 10^{-16}$   
 $\text{erg s}^{-1} \text{cm}^{-2}$   
 $20,000 (\text{deg})^2$   
 $0.5 < z < 2$   
 $\sigma_z/(1+z) = 0.001$

$\sigma_z/(1+z) > 0.01$ :  
Photo-z regime

Wang et al. (2010)

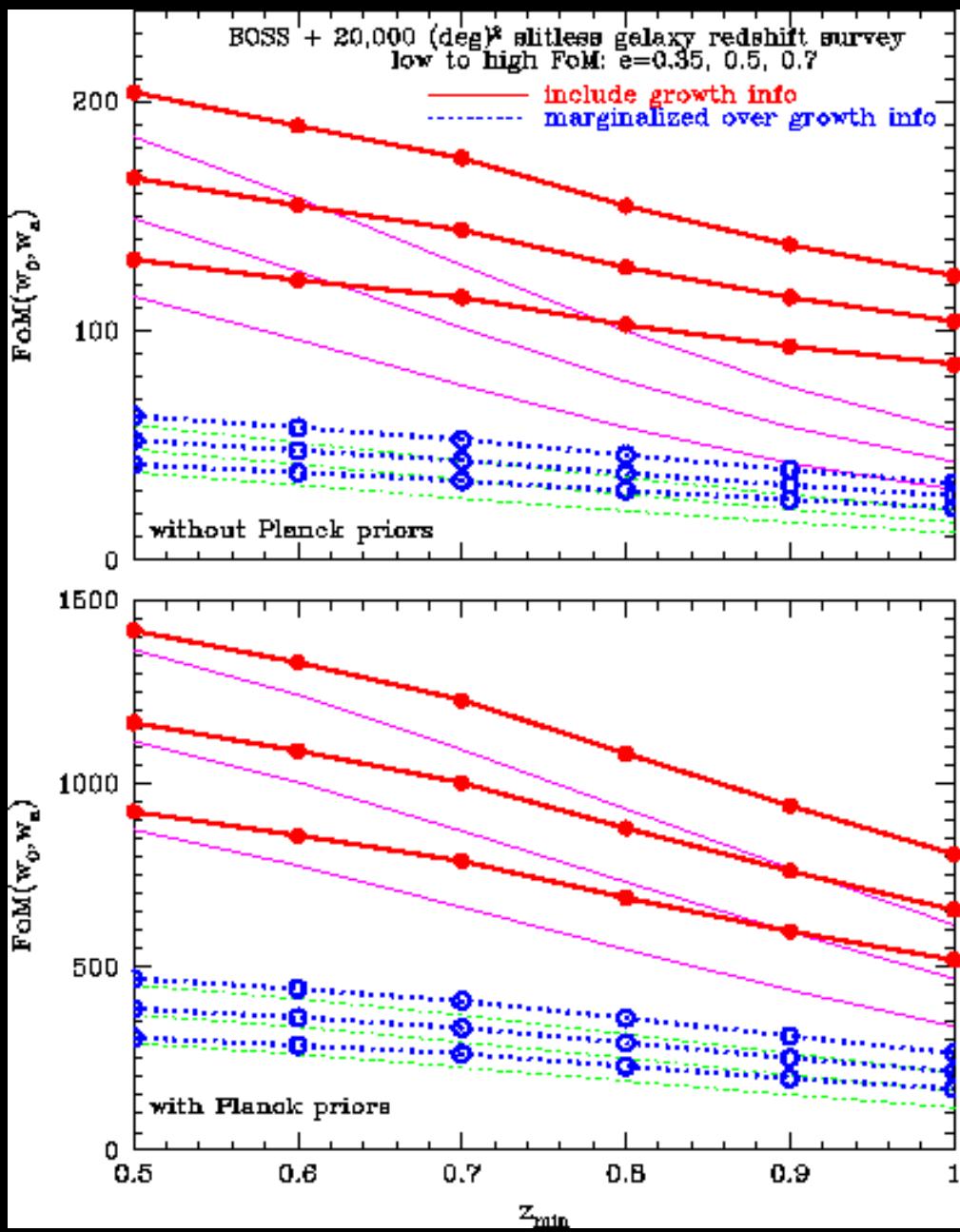


# Figure of Merit vs survey area

0.5 < z < 2

Wang et al. (2010)

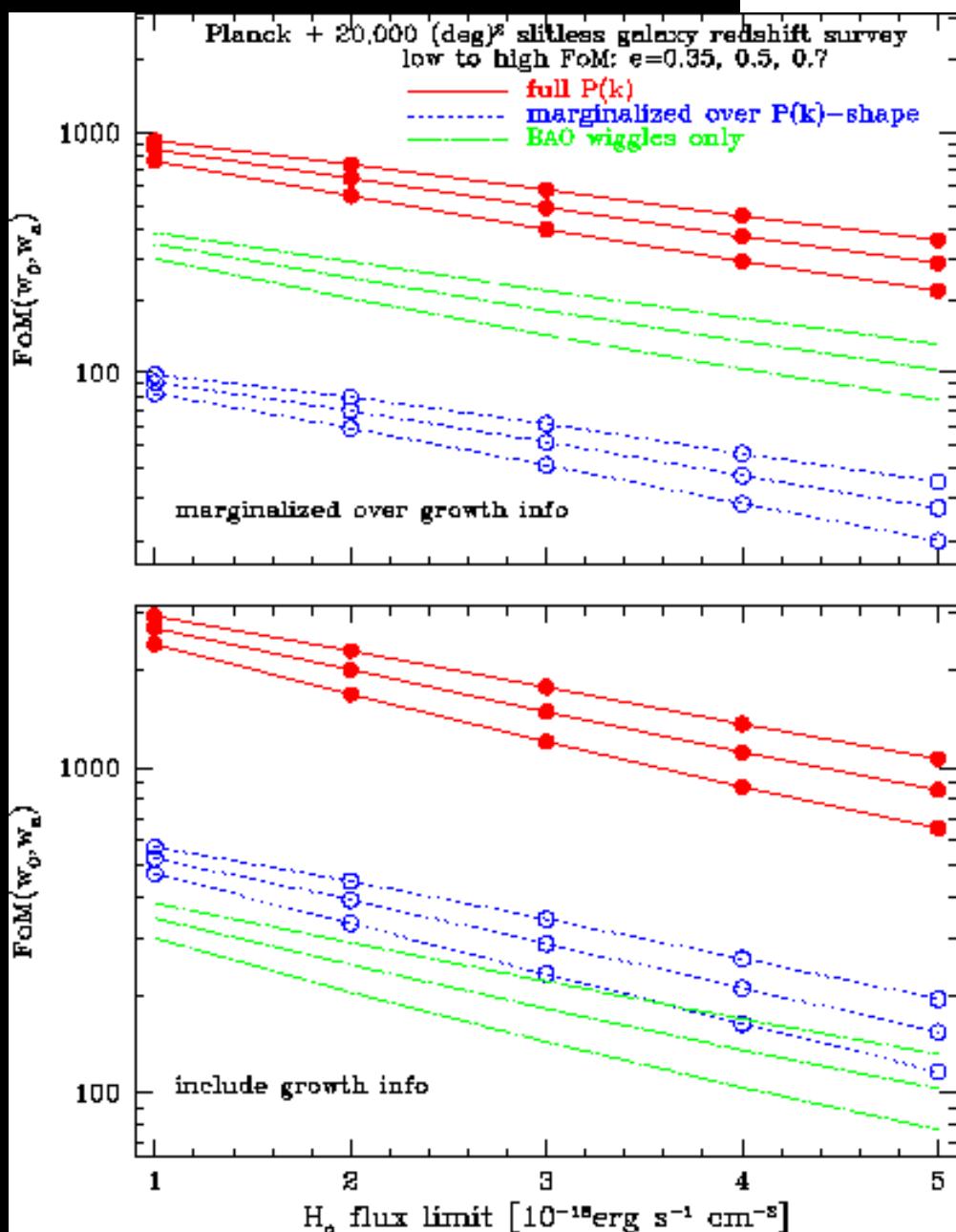
# Figure of Merit vs redshift range



BOSS +  
slitless  $z_{\min} < z < 2$

Wang et al. (2010)

# Figure of Merit vs forecast method



$$\sigma_z/(1+z)=0.001$$

Wang et al. (2010)

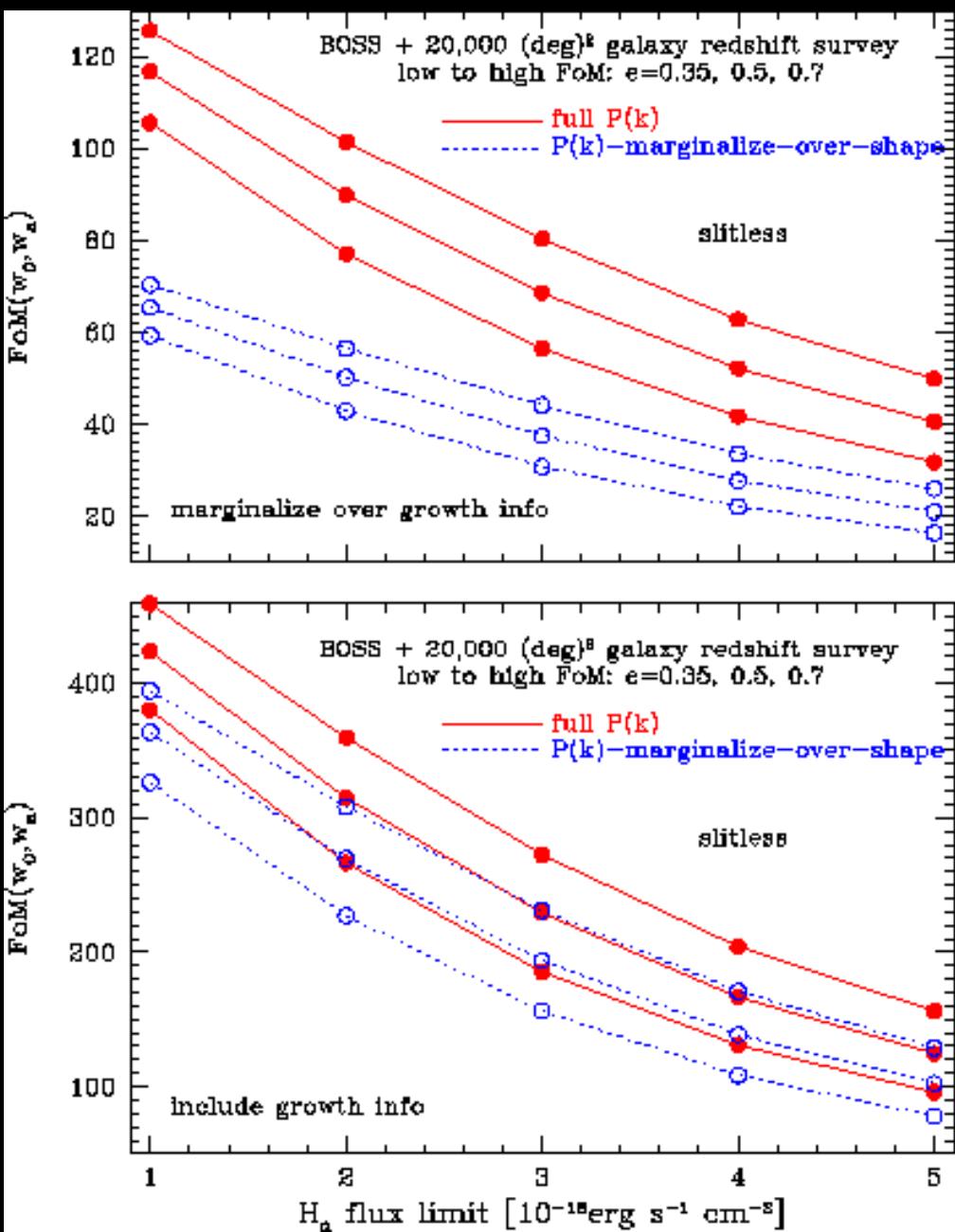
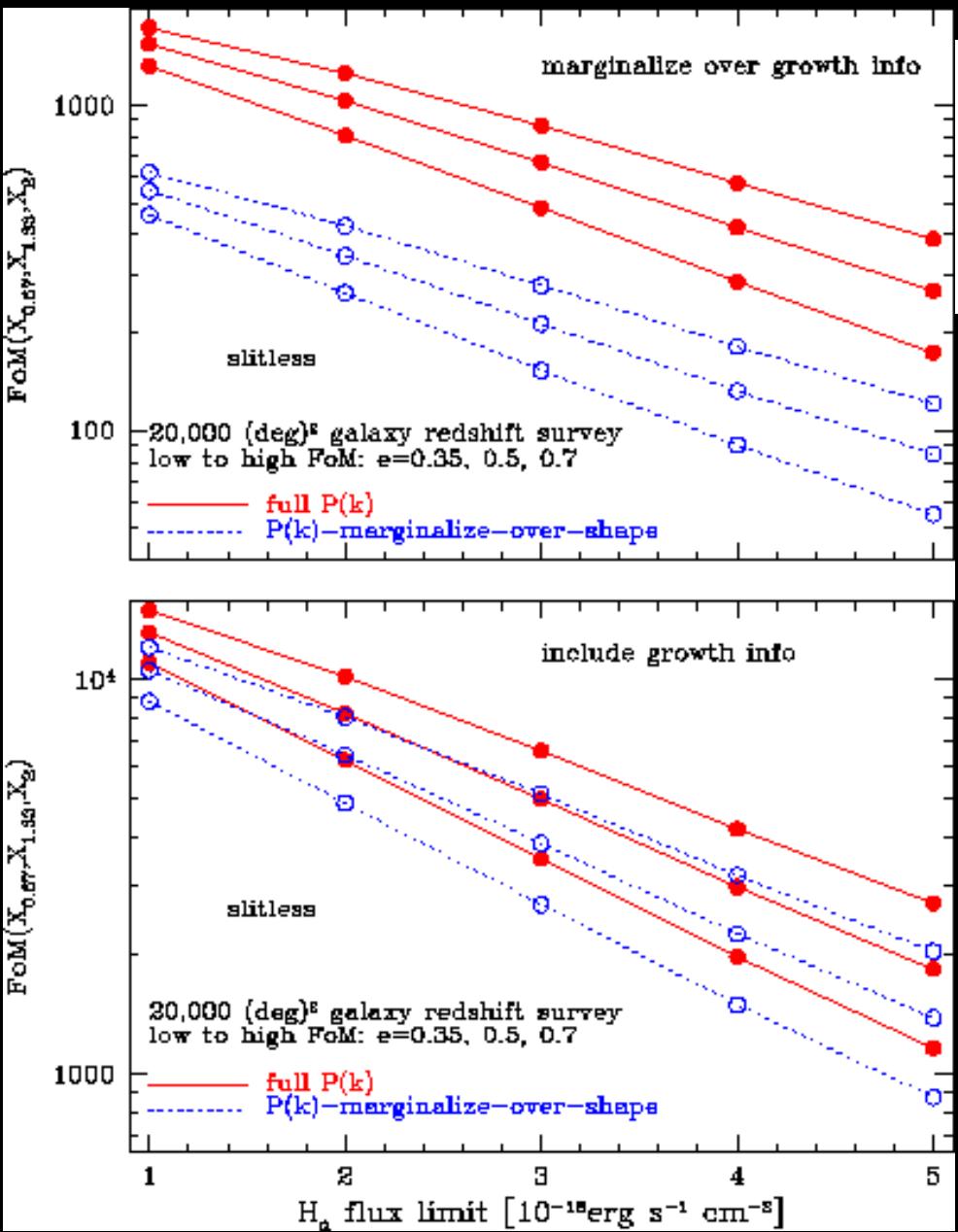


Figure of Merit  
vs flux limit

0.5 < z < 2

Wang et al. (2010)



FoM( $X_{0.67}, X_{1.33}, X_2$ )  
*vs flux limit*

0.5 < z < 2

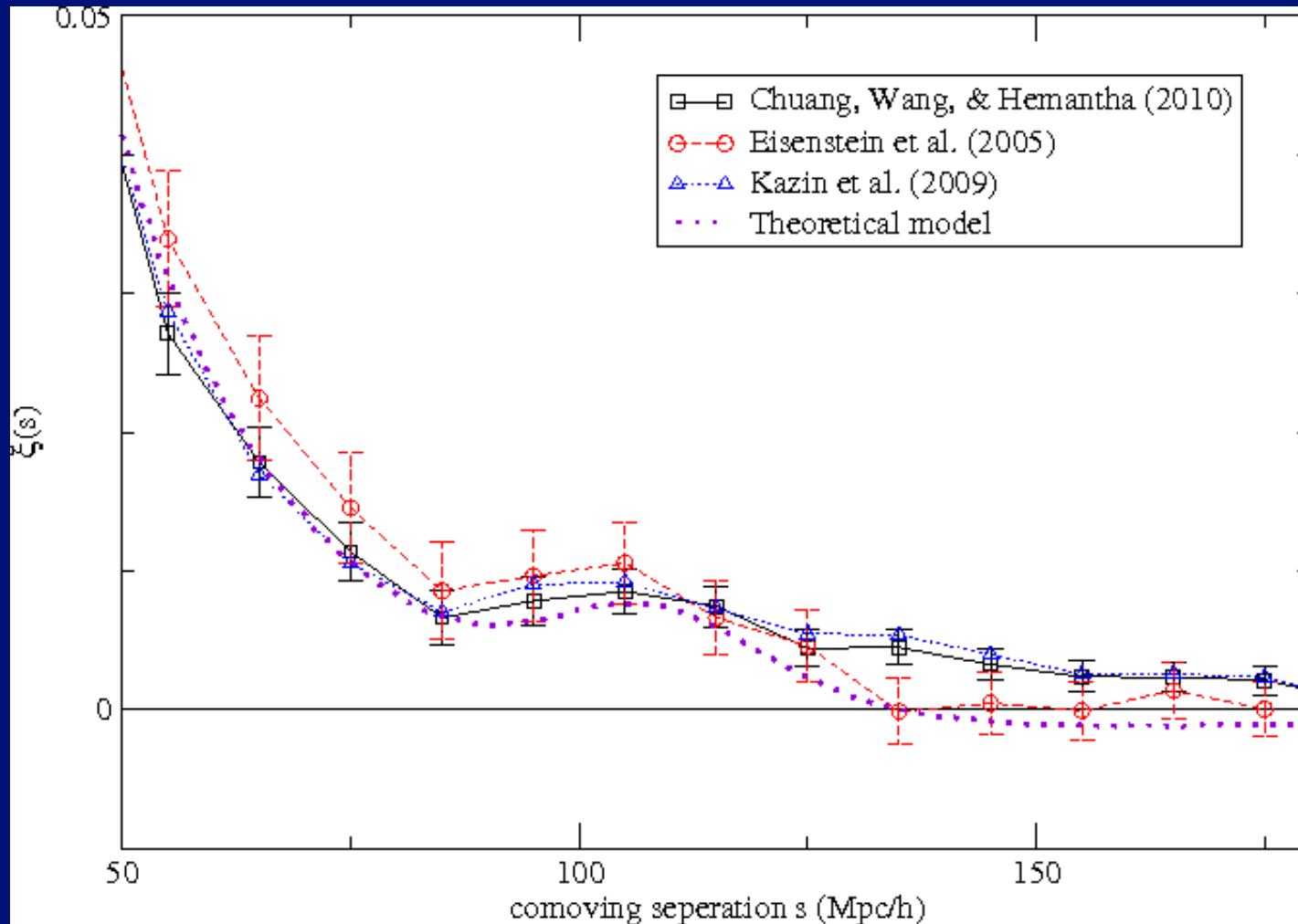
Wang et al. (2010)

# **The End**

# The Drag Epoch

- The BAO scale is the sound horizon scale at the drag epoch, when photon pressure can no longer prevent gravitational instability in baryons.
  - Epoch of photon-decoupling:  $\tau(z_*)=1$
  - Drag epoch:  $\tau_b(z_d)=1$ ,  $z_d < z_*$
  - The higher the baryon density, the earlier baryons can overcome photon pressure.
    - $R_b = (3\rho_b)/(4\rho_\gamma) = 31500\Omega_b h^2/[(1+z)(T_{CMB}/2.7K)^4]$
    - $z_d = z_*$  only if  $R_b = 1$
    - Our universe has low baryon density:  $R_b(z_*) < 1$ , thus  $z_d < z_*$   
(Hu & Sugiyama 1996)

# Puzzle: SDSS Large-Scale Clustering: Sample Variance or Unknown Systematics?



# More cosmology with the ENIS dataset

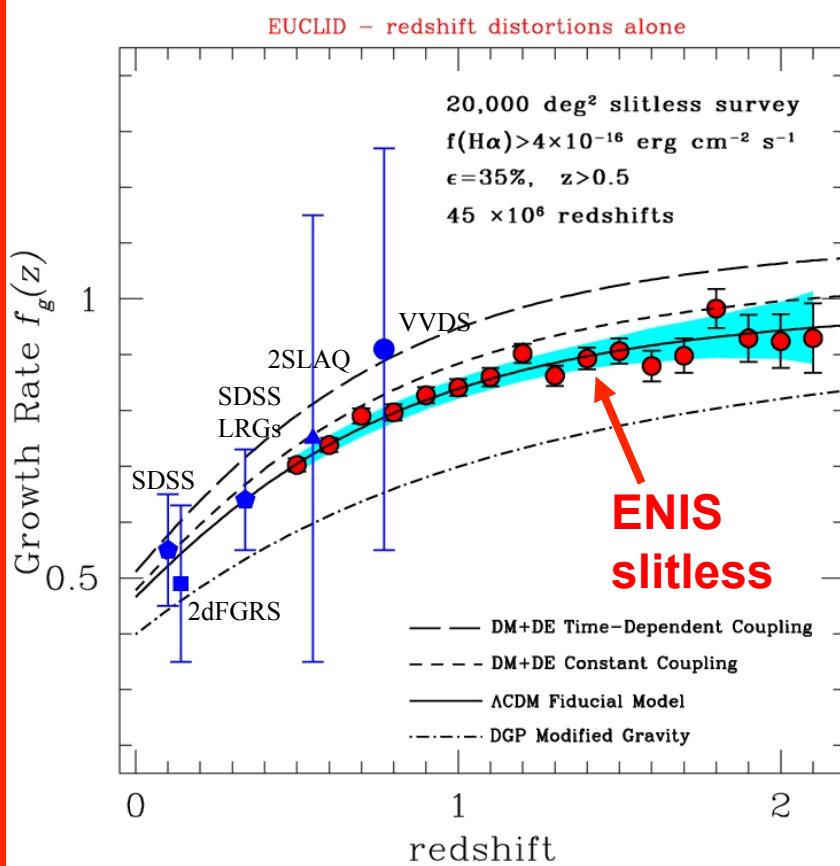
## Redshift Space Distortions

Anisotropy of radial vs tangential clustering

Impossible with photometric redshifts !

Test of Modified Gravity theories

Break degeneracies for models with same  $H(z)$



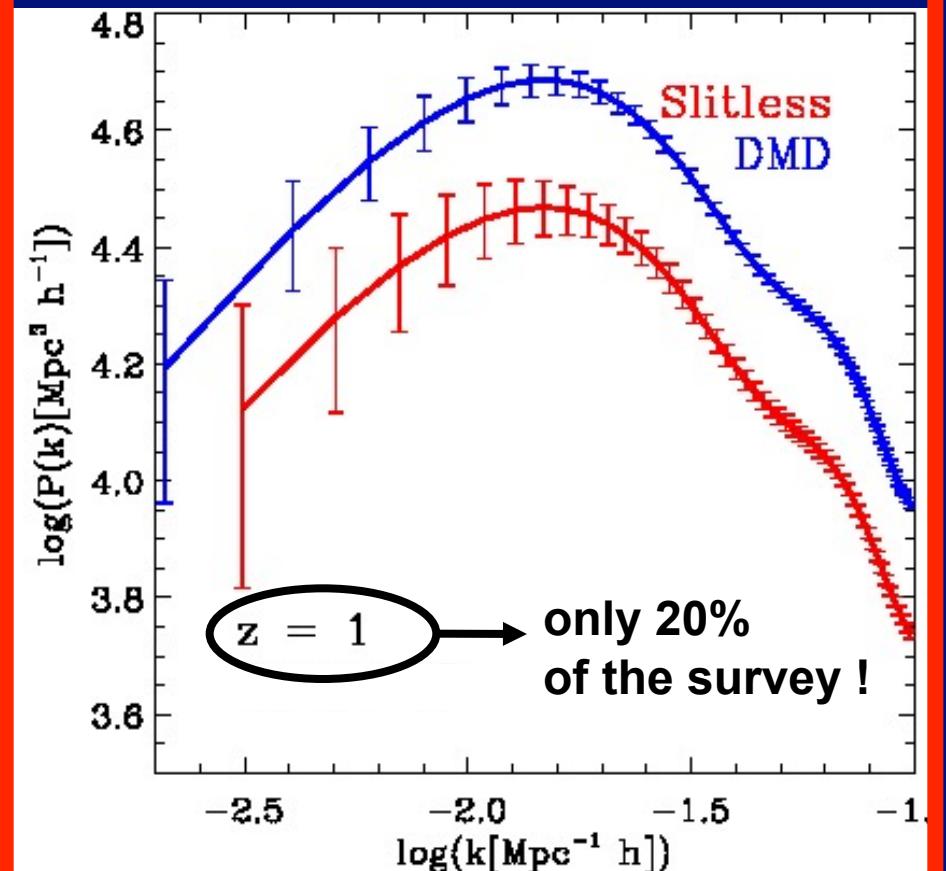
## Full Power Spectrum $P(k)$

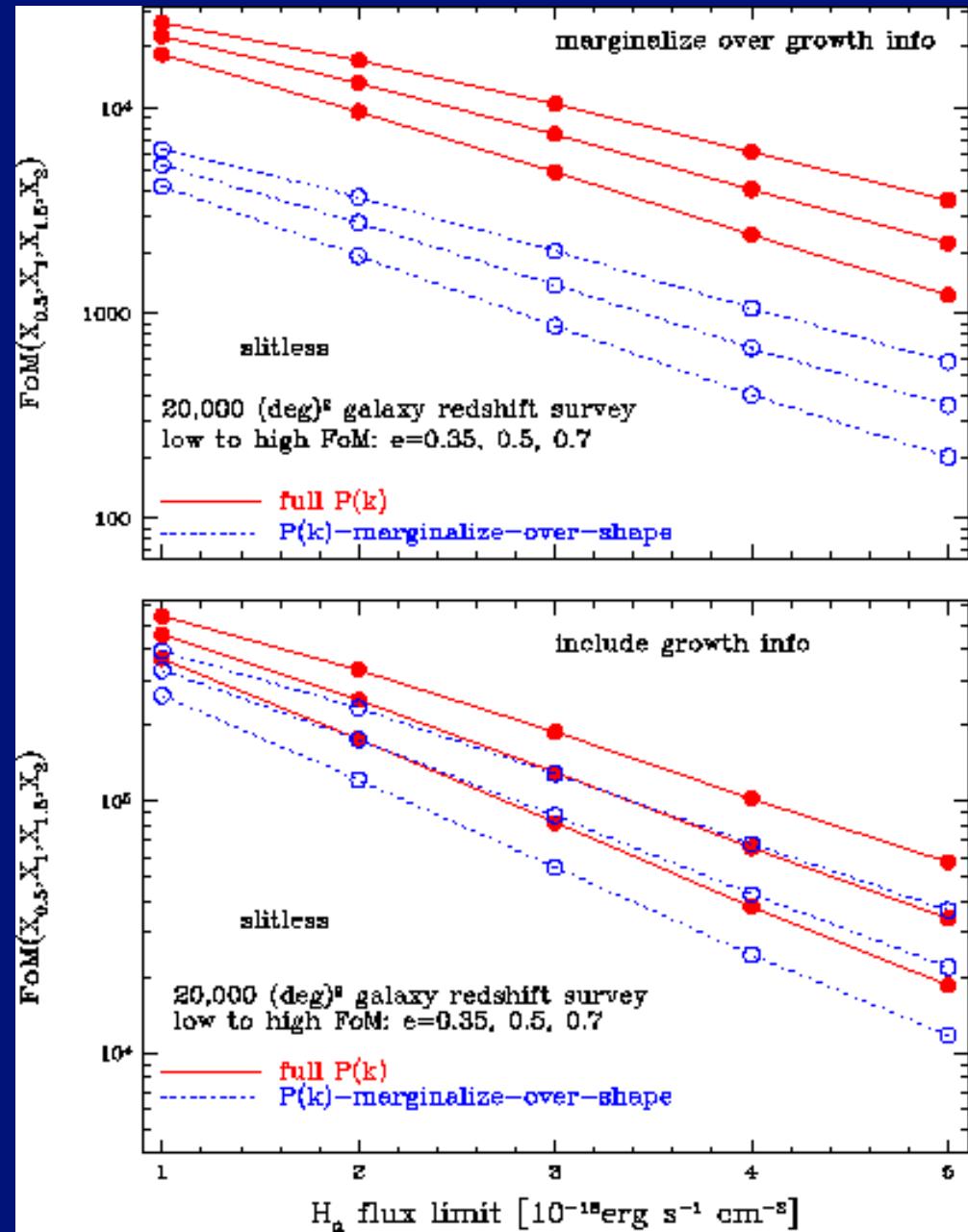
Primordial fluctuations

Models of inflation

Neutrino mass

Complementary to CMB





**FoM( $X_{0.5}, X_1, X_{1.5}, X_2$ )  
vs flux limit**

**0.5 < z < 2**